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THE BEHAVIOR OF LUBRICATION SYSTEM COMPONENTS IN A VACUUM ENVIRONMENT

by Donald H. Buckley
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at Second Aerospace Mechanisms Symposium sponsored by the University of Santa Clara, the Jet Propulsion Laboratory, and Lockheed Missiles and Space Company Santa Clara, California, May 4-5, 1967

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

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Studies have been conducted in a vacuum environment with the materials of concern in lubrication systems, namely, the lubricant and the material to be lubricated. Evaporation experiments have been conducted with various fluids, greases, inorganic compounds and soft metals in order to determine the influence of a vacuum environment on evaporation behavior. Friction, adhesion and wear experiments have been conducted with the various materials used in lubrication systems in an attempt to determine the influence of a vacuum environment on friction, wear and adhesion. The results of these studies have indicated that while relatively high rates of evaporation may be obtained for conventional oil and grease lubricants these materials may be effectively utilized if concepts such as molecular flow seals are used to reduce evaporative losses. Further, for prolonged exposure to vacuum environment, many inorganic compounds and soft metal films have potential usefulness. In addition to evaporation losses, concern must be provided for the type of lubricant that is used. With conventional lubricants degassing of the fluids can present a problem. The results of sliding friction experiments in a vacuum environment indicate that there are basic metallic structures which have markedly superior friction, wear and less tendency to adhere than now conventionally used bearing materials. Selective alloying of these metallic structures could be effectively used to prepare alloys specifically designed for use in lubrication mechanisms.

INTRODUCTION

In any lubrication system there are essentially two major components. These are the material surface to be lubricated and the lubricant. This applies to such complex systems as instrument bearing and gear assemblies as well as to such commonplace devices as latches and hinges. While the two basic components will generally remain relatively unchanged (namely, some type of lubricant and a material to be lubricated) the environment in which the system must operate may change. The environment may be normal air at atmospheric pressure and room temperature, cryogenic fluids, a corrosive media, operation at extremely high temperatures or a vacuum environment simulating space conditions. The task then of understanding the behavior of lubricating systems and their operation in various environments becomes one of understanding the influence of that environment on the lubrication system components.

The vacuum environment of space differs from the normal atmospheric environment in two major respects. First, the ambient pressures are appreciably reduced, and second, there is a lack of oxygen. There are other factors in a space environment such as radiation, solid particulate matter, and ionized and atomic species of gases. These latter characteristics are because of their levels and concentrations of only second order importance to lubrication systems.

The reduced ambient pressure of a space environment has two major effects on the lubricants in lubrication systems. It will degas the lubricant and will enhance evaporation. Degassing will remove such gases as oxygen and water vapor. These dissolved species have been shown to have a beneficial influence under severe boundary lubricating conditions (ref. 1). Evaporation may be a problem particularly with organic oils and greases, since complete evaporation

would result in the loss of one component of the system.

The absence of oxygen in a space environment could result in cold welding of mechanical components where lubricants are not present or have evaporated. Present day lubrication concepts include the presence of normal surface oxides and adsorbates on mechanical parts as a component of the integrated system.

The objective of this presentation is to examine the effects of a vacuum environment on the two major components of a lubrication system, the lubricant and the material to be lubricated. Some effects of vacuum on lubricants to be examined will include evaporation, degassing, and adherence of solid lubricant films. With respect to the material to be lubricated some of the properties to be examined will include the effects of reduced pressures, clean surfaces, metal structure, and selective alloying.

APPARATUS

A typical vacuum apparatus used in the measurement of friction and wear is shown in Fig. 1. The basic elements of the apparatus were the test specimens (2-1/2-inch-diameter flat disk and 3/16-inch-radius rider) mounted in a vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling consisted of two 20-pole magnets spaced axially 0.150 inch apart with a 0.30-inch diaphragm between magnet faces. The drive magnet outside the vacuum system was coupled to a low speed electric motor. The driver magnet was completely enclosed with a nickel-alloy housing (cutaway in Fig. 1) and was mounted at the upper end of the shaft within the chamber. The disk specimen was at the lower end of the shaft.

The rider specimen was supported in the specimen chamber by an arm mounted by gimbals and sealed by a bellows to the chamber. A linkage at the end of the retaining arm away from the rider specimen was connected to a strain-gage

assembly. The assembly was used to measure frictional force. Friction coefficients reported could be determined to within ± 0.005 . Load was applied through a dead-weight loading system. Directly opposite the load (at 180°) was a strain-gage assembly for measuring adhesion forces.

Attached to the lower end of the specimen chamber was a 500-liter-per-second ionization pump and a vac-sorption forepump. The pressure in the chamber adjacent to the specimen was measured with a cold-cathode ionization gage. Also present in the apparatus was a diatron-type mass spectrometer (not shown in Fig. 1) for determination of gases present in the vacuum system. A 20-foot, 5/16-inch-diameter stainless steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system. The vacuum chamber and specimens were baked out at 200 C for 16 hours prior to each experiment.

RESULTS AND DISCUSSION

Lubricants

The most severe effect that a vacuum environment simulating space conditions can generally have on lubricants particularly organic oils and greases is to markedly accelerate their evaporation rates. Detailed studies have been conducted in a vacuum environment simulating space conditions to determine the evaporation rates of various potential lubricating materials. These studies have been conducted under conditions such that the most severe type of evaporation is simulated, that is, there is no restriction to the evaporation process and for the molecules leaving the surface there is no return to the parent evaporating material. In the course of these studies many experiments have been conducted with various organic, inorganic and metallic lubricating materials (ref. 1-3). Figure 2 presents some summary data obtained

for various potential lubricating materials. This figure indicates the relative evaporation rates for various potential lubricants.

The oils and greases organic materials have the highest rates of evaporation. The inorganic compounds, such as molybdenum disulphide, have some of the lowest rates of dissociation or evaporation. Some metallic films, such as gallium indium and tin, have extremely low evaporation rates at moderate temperatures. The evaporation experiments of Figure 2 were all conducted at ambient temperatures of 200 and 400°F. At significantly higher temperatures or temperatures above 400°F the evaporation rates for the various lubricating materials can be expected to increase. Further, for some inorganic compounds dissociation may occur much more readily.

From the data presented in Figure 2, we can readily see that for long time space applications, it would certainly be desirable to utilize inorganic or metallic film materials as lubricants. While these materials have much lower evaporation rates than conventional oil and grease lubricants, they also have some notable limitations. Normally these materials are applied as thin films to the surfaces to be lubricated (ref. 4, 5 and 6). These films then have finite endurance lives. These lives frequently cannot be accurately predicted. In space mechanisms we must have the maximum in reliability. Therefore, a need for considerable improvement in the reliability of such coatings would be extremely helpful.

One of the most severe limitations of the presently used solid films is their poor adherence to the component to be lubricated. In a vacuum environment where outgassing of both substrate and coating can take place the problem is even more critical. Techniques are being currently developed for the application

of metallic and inorganic compounds without the use of binders and with markedly superior adherence to presently used coatings (ref. 5 and 6).

In using conventional organic oil and grease lubricants a number of techniques have been devised to reduce the loss of lubricants due to the evaporation from a space mechanism. One such device has been the utilization of molecular flow seals. The use of molecular flow seals can markedly reduce the evaporative loss of oil and greases from components to be lubricated. This means of reducing evaporation can be quite effective and provide for effective lubrication of mechanical components for long periods. For example, in the Tiros II satellite, bearings operating successfully for over one year with a conventional ester lubricant utilizing the molecular flow seal concept (ref. 7). This approach appears very attractive for use with conventional lubricants such as oils and greases. With organic fluids it would be of interest to know what effect the molecular weight for a particular species of a fluid has on its evaporation characteristics. From the Langmuir equation one might predict that the evaporation rate for an oil or grease might be a function of its molecular weight. A series of evaporation experiments were conducted in vacuum with a polyalkylene glycol group of fluids in which each constituent fluid had a different molecular weight. The results of some evaporation experiments conducted in vacuum with this series of fluids are presented in Figure 3. Examination of Figure 3 indicates that the higher the molecular weight of the fluid the lower is the evaporation rate. Further, Figure 3 is a plot of evaporation rate as a function of temperature and the higher the molecular weight of the fluid the higher the temperature to which the fluid can be effectively utilized in a vacuum environment.

A vacuum environment stimulating space conditions not only markedly influences the evaporation properties of the lubricating materials but also has a marked effect upon the removal of gaseous constituents dissolved in the lubricating materials (ref. 8). In order to determine what effect degassing or the removal of these gaseous species would have on the lubricating properties of the fluids, some experiments were conducted with fluids which were used as received and the same fluid after a thorough degassing to remove such gaseous species as oxygen and water vapor. Results obtained in friction and wear experiments with two typical fluids, a polyphenyl ether and a chloromethyl silicone are presented in Figure 4.

The data of Figure 4 indicate that for the polyphenyl ether degassing markedly influences the friction and wear properties of the fluid. An increase in friction and wear was observed with the degassed polyphenyl ether fluid. With the chloromethyl silicone, however, degassing did not markedly alter the friction behavior of the fluid in lubricating nickel. With this fluid a decrease in wear was observed with degassing. The reason that polyphenyl ether may be markedly influenced by degassing and the chloromethyl is not may rest with the presence of the chlorine in the chloromethyl silicone. The chlorine in the molecule acts as an extreme pressure lubricant at the sliding interface providing for effective boundary lubrication due to formation of inorganic metallic chloride films. The presence of oxygen and water vapor does not improve the lubricating properties of this fluid. With the polyphenyl ether, however, no reactive atoms such as chlorine are present in the molecular configuration and the fluid itself is inherently a poor lubricating material. Its ability to lubricate is reduced appreciably by removal of dissolved gases which contain constituents which might normally react with the surface to form extreme pressure boundary lubricants.

From the results presented thus far it becomes somewhat evident that a vacuum environment simulating space conditions certainly influences the evaporation properties of lubricants and secondly that the vacuum environment of space reduces appreciably the presence of dissolved gases from normal lubricants.

Materials for Mechanical Components of Lubrication Systems

The materials providing lubrication for mechanical components of space mechanisms are important, but of equal importance are the materials to be lubricated. These materials can take the form of bearings, gears, seals, latches, or some other mechanical device. In general, some type of lubrication is provided to adequately handle the lubrication of the mechanical component during its operation. There is, however, always the possibility that the lubricant will be lost from the system due to evaporation or some other process which could result in metal to metal contact. Even if a complete loss of a lubricant does not occur, and boundary lubricating conditions exist, a certain amount of metal to metal contact through the lubricating film will occur. It, therefore, is important to understand the friction, adhesion and wear behavior of the mechanical component materials in the absence of lubricants.

In order to determine the influence of reduced ambient pressures on the friction properties of a material, a series of friction experiments were conducted in a vacuum environment with the very commonly used bearing steel 52100. In the initial experiments, sliding friction experiments were conducted to determine the influence of reducing the ambient pressure on friction coefficients. The results obtained in one such series of experiments are shown in Figure 5.

The data of Figure 5 indicate that relatively high friction coefficients, approximately .5, are obtained for 52100 bearing steel in sliding contact with itself. As the ambient pressure is reduced however the friction coefficient decreases to a minimal value in a pressure region 10^{-4} to 10^{-6} torr. The friction coefficient then begins to increase.

The high friction coefficient at ambient pressure of 760 torr may be associated with the presence of the higher oxides of iron on the metal surface, namely, Fe_2O_3 . As the pressure is reduced, however, less oxygen and water vapor are available for reaction with the metallic surface. As a consequence, the lower oxides of iron, namely, Fe_3O_4 and FeO , are formed. These oxides have much better lubricating properties than the higher oxide of iron (Fe_2O_3) and as a consequence a reduction in friction coefficient is observed. If, however, the pressure is further reduced insufficient oxygen becomes available to form a continuous surface film and as a consequence an increase in metal to metal contact occurs with an increase in friction coefficient.

If a similar sliding friction experiment with 52100 in sliding contact with itself is conducted with liquid helium cryopumping of the vacuum chamber to reduce the oxygen concentration friction results similar to those shown in Figure 6 are obtained. In Figure 6 the friction coefficients initially for 52100 in sliding contact with itself were relatively low, approximately 0.5. With increasing time, however, the residual surface oxide is worn away and oxygen is not available to reform the surface film. As a consequence, the friction coefficient increases very rapidly and ultimately reaches a value in excess of 5.0 at which point complete welding of the two specimens occurred. The results presented in Figures 5 and 6 with a commonly used bearing steel 52100 indicate the importance of residual surface oxides and contaminating films on the friction behavior of mechanical components of lubrication systems.

It would be desirable to have materials in mechanical components of lubrication systems with inherently low friction and wear characteristics. These materials would certainly be desirable for use in such systems to prevent the possible catastrophic welding that is observed with conventional materials such as 52100 bearing steel in the absence of lubricating films. In the course of some of our studies with simple unalloyed metals it was found that while conventional cubic metals (body centered cubic and face centered cubic metals) will exhibit very high friction coefficients, adhesion and complete welding in a vacuum environment, hexagonal metals and alloys do not exhibit the same tendency. The results obtained in some typical friction experiments with various cubic and hexagonal metals are presented in Figure 7.

The data of Figure 7 indicate that for the conventional face centered cubic metals, copper and nickel, in sliding friction experiments in a vacuum environment very high coefficients of friction and complete welding of the metals will occur. With the hexagonal metals, such as beryllium, however, complete welding was not readily observed. Note particularly the relatively low friction characteristics for the hexagonal metal beryllium. It appears that crystal structure has an influence on the friction properties of metals in contact. Any metal which exhibits allomorphic characteristics, that is, transforms from one crystal form to another should exhibit marked changes in friction properties with changes in crystal structure. A metal which is of considerable interest for lubrication systems applications is the metal cobalt. Cobalt has an allomorphic transformation. It transforms from a close packed hexagonal to a face centered cubic structure at a temperature of

approximately 800°F. In order to determine if the transformation in cobalt from the hexagonal form to the cubic form would in fact exhibit an influence on friction properties for cobalt, friction experiments were conducted in vacuum with cobalt in sliding contact with itself. Results of one such series of experiments are presented in Figure 8.

The data of Figure 8 indicate with cobalt in its hexagonal form the friction coefficients are relatively low, approximately .3. It is interesting to note that these friction coefficients are lower than those obtained with 52100 in sliding contact with itself in air at 760 torr. If, however, the temperatures are increased to near that of the crystal transformation from the closed packed hexagonal to face centered cubic form, a marked increase in friction is observed. Ultimately complete welding of cobalt to cobalt occurs. If, however, after welding the specimens are separated and allowed to cool to room temperature the initial friction coefficients obtained for cobalt are once again observed. These results indicate the reversibility of the cobalt crystal transformation.

In addition to the friction coefficients being markedly influenced by the crystal transformation from a closed packed hexagonal to a face centered cubic form wear for cobalt is also markedly influenced. Wear measurements made at two temperatures, one for cobalt and its hexagonal form, and the second during the transformation, indicate a hundred fold difference in the adhesive wear rates for cobalt in the two crystalline forms. The data of Figure 8 then, with that of Figure 7, indicate that crystal structure certainly does influence the friction and wear behavior for metals in the absence of surface films.

The desirable friction and wear characteristics for the hexagonal metals were deemed worthy of further investigation. Detailed studies were, therefore, conducted with various hexagonal metals in sliding contact with themselves and conventional bearing steels in a vacuum environment to determine if any differences would exist in the friction properties for various hexagonal metals. In the course of these studies, a relationship was found to exist between the friction properties of various hexagonal metals and their crystallographic slip behavior. Detailed studies with single crystals of hexagonal metals with various crystallographic planes oriented parallel to the interface indicated that in hexagonal metals the preferred slip planes, that is the slip planes of highest atomic density, exhibited the lowest friction characteristics. Since crystallographic slip behavior in hexagonal metals is dependent upon lattice parameters, it was felt that some relationship must exist between friction coefficients and the lattice parameters for hexagonal metals. Detailed friction experiments with a number of hexagonal metals having various lattice parameter ratios were conducted in a vacuum environment. The results of some of these experiments are presented in Figure 9.

In Figure 9 the friction coefficients for various hexagonal metals in sliding contact with 440-C stainless steel are plotted as a function of the inter-basal planar spacing over lattice parameter " a " for various hexagonal metals. The term inter-basal planar spacing is used rather than the c/a lattice ratio because for a number of hexagonal metals in the rare earth series more than a single set of basal planes are present in the cell. The results of Figure 9 indicate a direct relationship exists between the lattice parameters

of hexagonal metals and their friction properties. Slip behavior, during mechanical deformation, can be correlated for various hexagonal metals with the c/a lattice ratio. Those metals exhibiting c/a lattice ratios near the ideal stacking sequence for atoms in hexagonal metals, namely 1.633, exhibit predominantly basal slip mechanisms while those which deviate considerably such as titanium, zirconium and hafnium, exhibit predominantly prismatic and secondarily pyramidal slip mechanisms.

Although beryllium has a lattice ratio which deviates considerably from the ideal stacking ratio, it slips predominantly on basal planes accounting for its relatively low friction coefficients despite its position on the curve of Figure 9.

The data of Figure 9 are certainly interesting. The question, however, which arises is how can these data be effectively utilized to reduce the friction properties and adhesion tendencies of bearing materials. A practical application of the curve presented in Figure 9 might be to selectively alloy various hexagonal metals to improve their friction characteristics. For example, in space systems titanium is a metal frequently considered for use. However, because of mechanical strength considerations it is most frequently used in the form of cubic alloys. Titanium has notoriously poor friction and wear properties and is extremely prone to cold weld.

There are, however, a number of alloying elements that can be added to titanium to expand the c/a lattice ratio in titanium bringing it closer to the ideal stacking sequence for basal slip hexagonal metals such as cobalt (ref. 9). Some of these alloying elements are oxygen, tin and aluminum. Experiments were conducted, therefore, with titanium to which varying percents of two

elements were added. In one series of experiments a simple binary series of titanium-tin alloys were prepared and in the second series of experiments, a series of titanium-aluminum alloys were prepared. The alloying material was added to titanium to maximum solubility. Care was taken to avoid the formation of second phases. X-ray determinations were made for the lattice parameters of the hexagonal binary titanium alloys formed. Friction experiments were also conducted with these alloys. Lattice parameters and friction coefficients for these alloys in sliding contact with themselves are presented in Figure 10. The results of Figure 10 indicate that as the c/a lattice ratio for titanium-tin and titanium-aluminum alloys increases the friction coefficient decreases. These results would indicate then, that selective alloying can be utilized to reduce the friction properties of metals.

In addition to altering the lattice parameters for hexagonal metals by selective alloying the crystal transformation temperatures in some instances for hexagonal metals can also be altered. For example, the addition of 25 weight percent molybdenum to the hexagonal metal cobalt can increase the transformation temperature appreciably. If a hexagonal metal is considered for use at somewhat elevated temperatures and it is desirable to retain the hexagonal crystalline form to these higher temperatures selective alloying with elements such as molybdenum may be effectively utilized to achieve desirable friction properties over a broader temperature range. Some simple binary cobalt-molybdenum alloys were prepared. A 25 weight percent molybdenum in cobalt alloy was used in sliding friction experiments to determine if, in fact, elevating the crystal transformation temperature would have an effect on friction properties. The results obtained in some sliding friction experiments

together with data for unalloyed cobalt are presented in Figure 11. The data of Figure 11 present the coefficients of friction for the cobalt-molybdenum alloy as a function of sliding velocity. With increased sliding velocity increases in interface temperature occurs. In a range, where a marked change in friction properties for cobalt was observed in sliding contact with cobalt, a change in the friction properties for the cobalt molybdenum alloy did not occur. These results, then, indicate that such selective alloying techniques can be effectively utilized to retain a desirable hexagonal form for metals over a broader temperature range.

The results presented in Figures 10 and 11 indicate that by selective alloying we can improve the friction behavior characteristics for elemental metals. While these studies were conducted with simple binary alloys which by no means represent bearing compositions or materials for gear applications they do, however, point to a direction in which the formulation of alloys may be made with the intent of the alloy being specifically designed for lubrication systems. That is, the alloy has inherently good friction, wear and low adhesion properties. These properties are designed into the alloy in its formulation. This would seem to be a much more desirable approach to the use of materials in lubrication systems than the most frequently and conventional used technique of simply obtaining alloy compositions from other scientific fields of endeavor, such as the tool steel industries. In a vacuum application or extreme vacuum environment in space conditions it certainly would be desirable to have the low friction, wear and adhesion properties of the hexagonal metals and alloys in the event of lubrication failure.

In addition to the alloying concepts provided in Figures 10 and 11, other mechanisms have been effectively utilized to reduce the friction, wear and adhesion properties of alloys. Such concepts as alloying with inclusion compounds in materials to reduce the friction properties have been effectively utilized. For example, sulphur has been effectively added to conventional bearing steels to replace in the process of sliding contact the normally formed metal surface oxides (ref. 10). In these alloys an inclusion compound is built into the alloy structure to replace surface films when they are worn away. Another alloy concept which can be effectively utilized to reduce friction properties of materials in a vacuum environment is that of the old lead copper bearing concept. This concept however has been updated to include some high temperature alloy systems and solid lubricants (ref. 11). Again, this type of selective alloying approach can be effectively utilized to reduce the friction, wear and adhesion behavior of materials in contact. This not only applies to materials in contact in the absence of lubrication but also under boundary lubricating conditions where some metal to metal contact will occur.

CONCLUDING REMARKS

The discussion in this presentation has dealt with the two major components involved in lubrication systems intended for use in a space environment, namely, the lubricant and material to be lubricated. With respect to the lubricant concern must be given to the accelerated evaporation of lubricant materials in a vacuum environment simulating space conditions. Further, the influence of the vacuum environment on degassing conventional lubricating materials such as oils and greases can also markedly alter their performance

characteristics. In addition, with the application of solid film lubricating materials such as inorganic compounds and soft metallic films extreme care must be taken to provide for adequate adherence of these films to the substrate materials. Adherence of these coatings to the substrate material will determine to a large extent the effectiveness of these coatings in providing lubrication for long periods.

In reference to the materials to be lubricated a considerable improvement in friction, wear and reduction in the adhesion tendencies may be obtained from materials of lubrication systems if selective alloying or duplex alloying concepts are utilized. Conventional bearing materials will weld readily in a vacuum environment simulating space conditions. There are, however, alloy structures with basic hexagonal crystal forms which have much less tendency to cold weld in a vacuum environment. These systems certainly offer considerable promise for use in advanced spacecraft devices. The data of this presentation discusses the two components of a lubrication system. It must be indicated, however, that an interrelationship between the lubricant and the material to be lubricated exists and this must also be considered in any study of lubrication systems.

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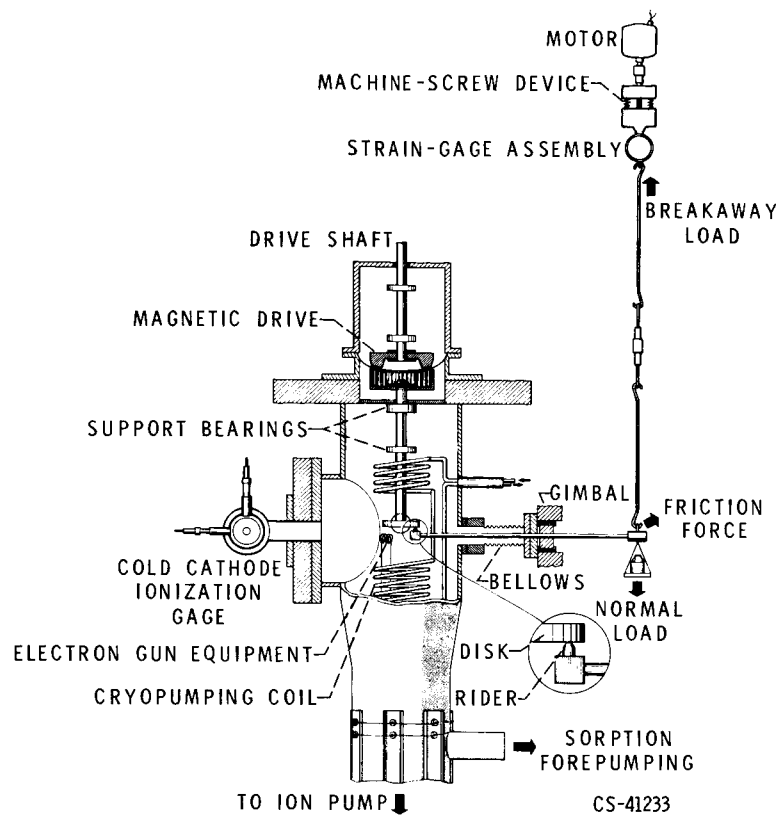
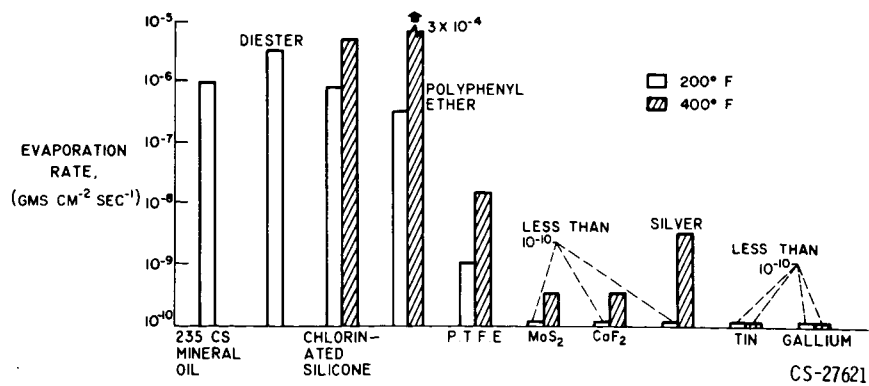


Figure 1. - Vacuum friction apparatus.

Figure 2. - Evaporation rates for various materials in vacuum. Ambient pressure, 10⁻⁶ - 10⁻⁷ mm Hg.

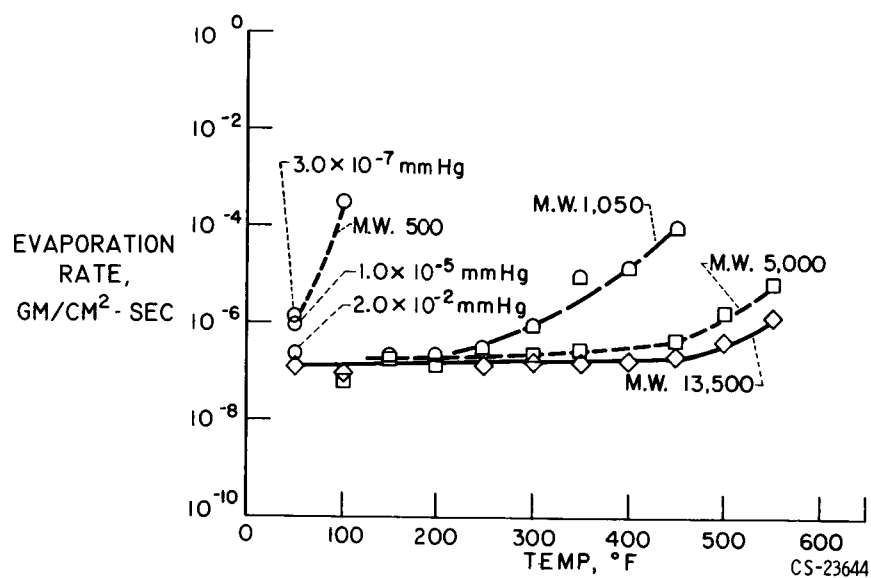


Figure 3. - Evaporation rates for various molecular weights of polyalkylene glycol. Ambient pressure 10⁻⁷ mm Hg.

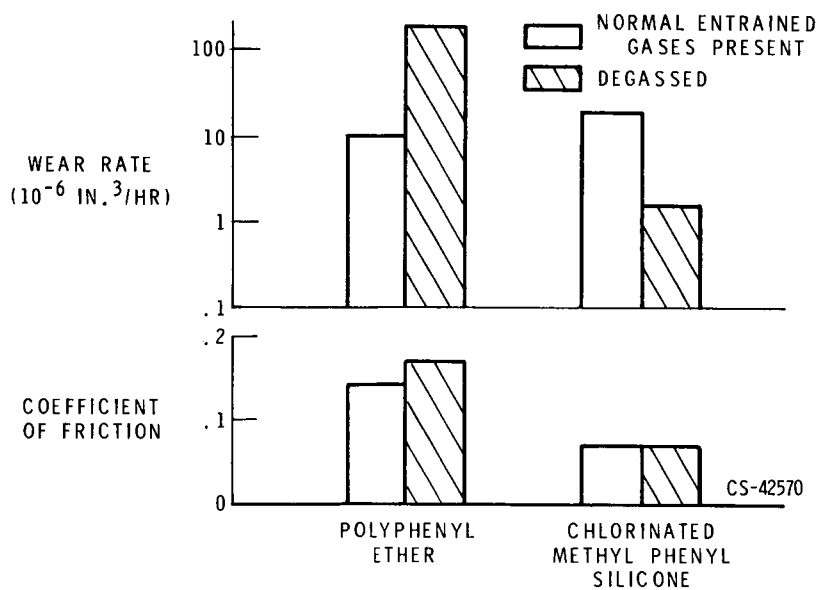


Figure 4. - Effect of gases entrained in oils on friction and wear of nickel.

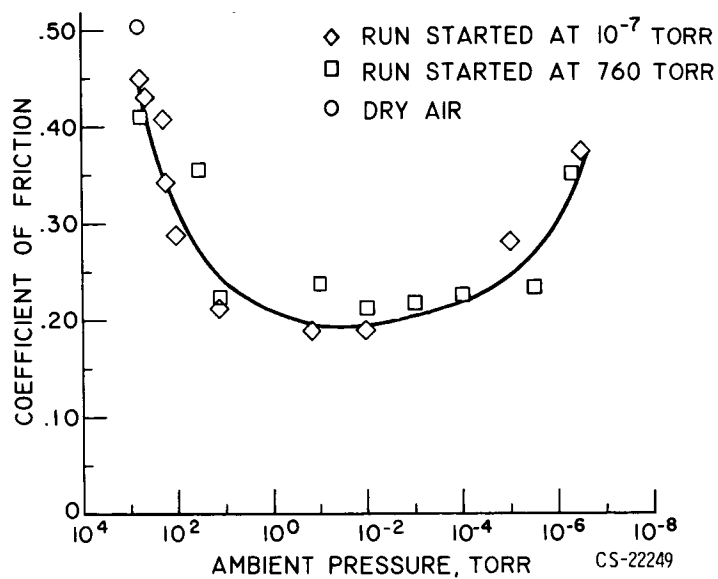


Figure 5. - Coefficient of friction for 52100 sliding on 52100 at various ambient pressures. 390 ft/min; 1000 g; 75° F.

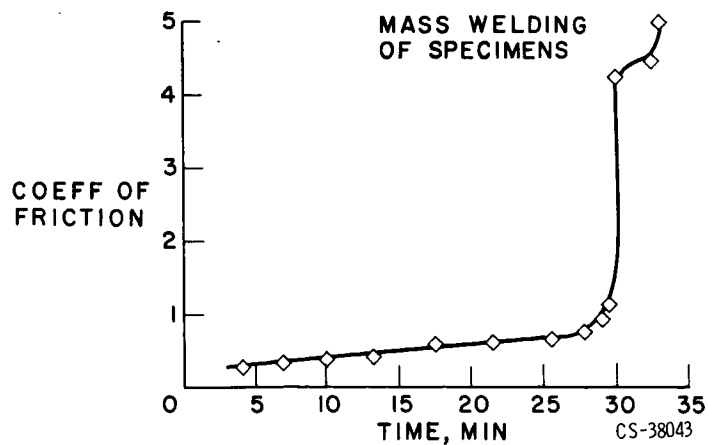


Figure 6. - Friction of 52100 sliding on 52100 in vacuum. 390 ft/min, 1000 G.

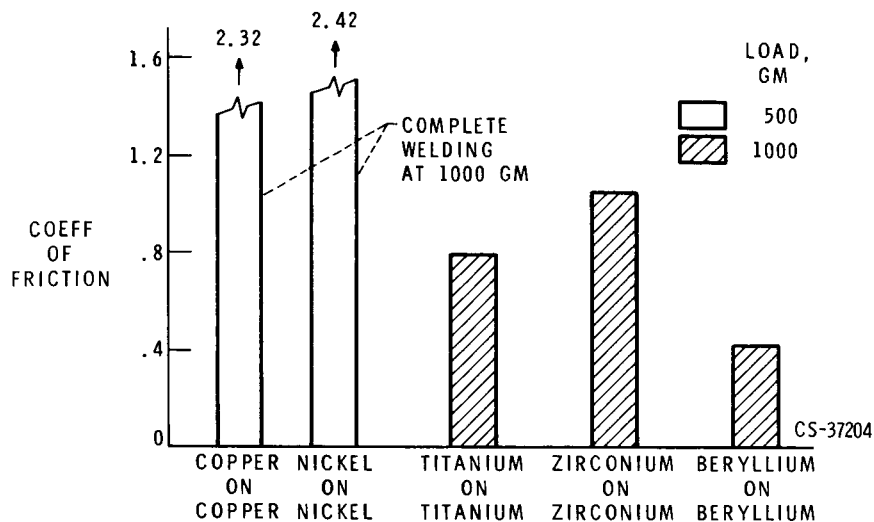


Figure 7. - Coefficient of friction for various metals in vacuum 10^{-9} mm Hg, 0.025 cm/sec, 25° C.

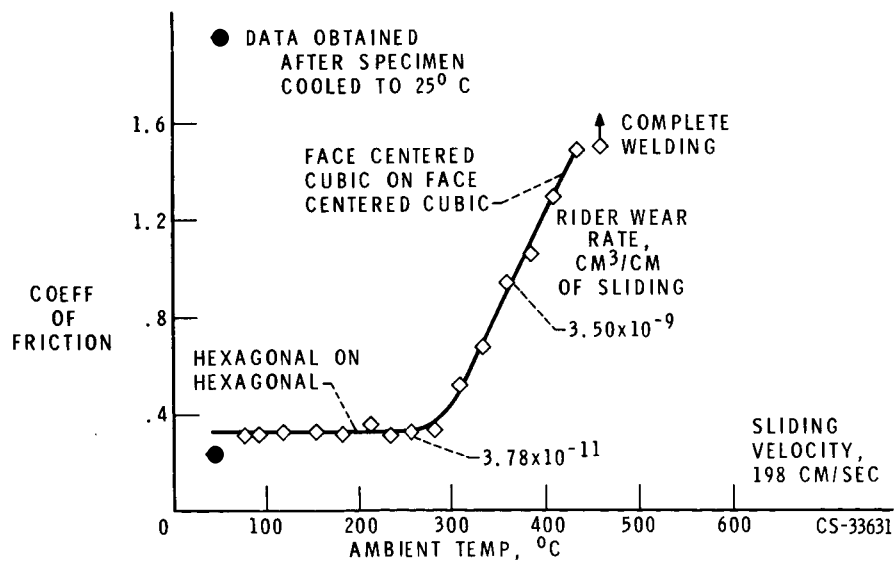


Figure 8. - Coefficient of friction for Co sliding on Co in vacuum at various temperatures. 10^{-9} mm Hg, 1000 gm.

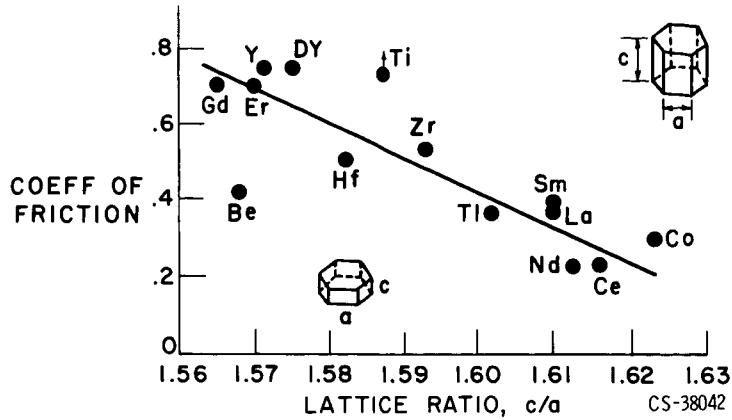


Figure 9. - Friction of various hexagonal metals. 10^{-9} mm Hg; load, 1000 g; 390 ft/min, on 440C steel.

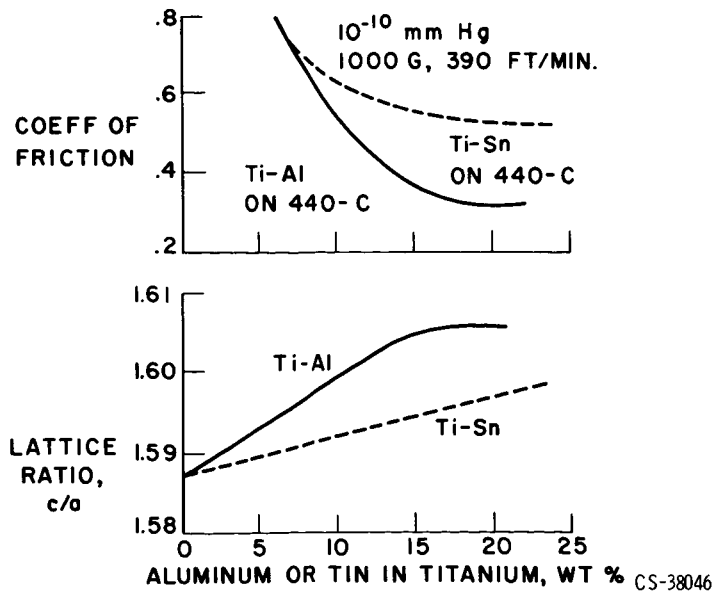


Figure 10. - Friction and lattice ratio (c/a) for titanium alloys.

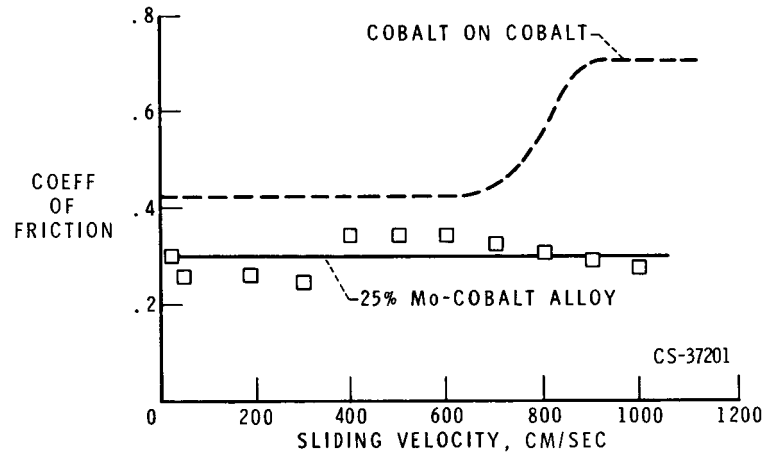


Figure 11. - Coefficient of friction for Mo-Co alloys sliding on disks of the same material in vacuum. 10^{-9} mm Hg, 1000 gm, 25° C.